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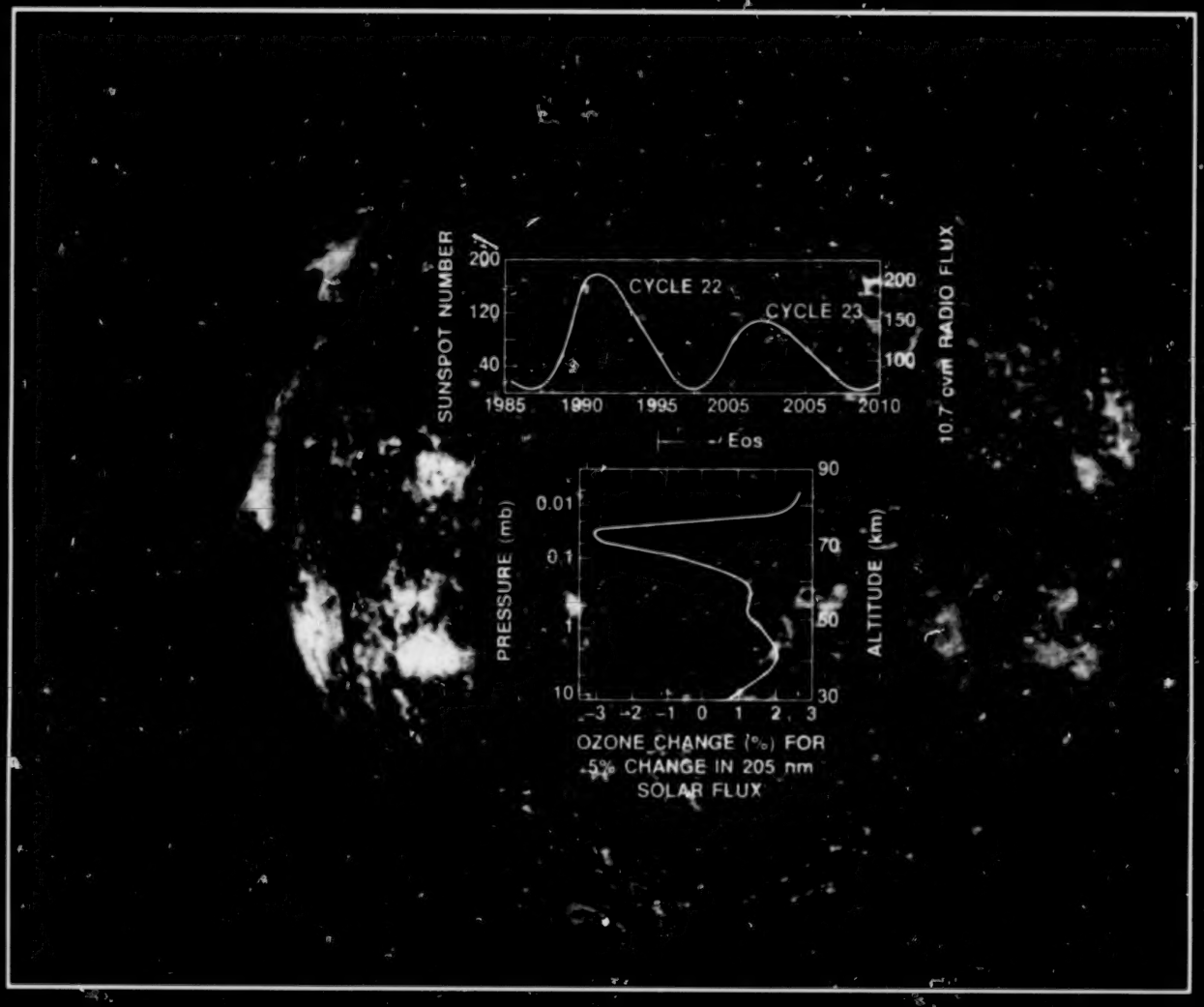
SUSIM

Naval Research Laboratory



A Program to Study the Sun's Interaction with the Upper Earth Atmosphere

to be flown on the
UARS and ATLAS Missions
National Aeronautics and Space Administration

COMPLETE!

ON THE COVER:

On December 19, 1973, the NRL spectroheliograph flown on NASA's Skylab viewed the Sun, showing regions of enhanced ultraviolet emission at 30.4 nm (He II). The fraction of the Sun's disk covered with these active regions, which are enhanced in emission at all ultraviolet wavelengths, increases with solar activity, as measured by the sunspot number and the 10.7 cm radio flux. The predicted variations in the sunspot number and the 10.7 cm flux during solar activity cycles 22 and 23 are shown. At the maximum of the Sun's 11-year cycle, when many bright areas appear on the Sun, the ultraviolet emission is increased above its value at times of minimum activity. These changes in solar ultraviolet radiation cause variations in the Earth's ozone concentration. The response of atmospheric ozone to a 5% change in the solar irradiance at 205 nm is shown.

CONTENTS

2	*The Solar Cycle and Solar Magnetism*
6	*Why Does the Sun's Radiation Change?*
8	*Is there a Connection Between the Solar Cycle and the Weather and Climate on Earth?*
10	*The Sun and Upper Layers of Earth's Atmosphere*
12	*Solar Ultraviolet Radiation and Processes in the Upper Atmosphere*
14	*The SUSIM Experiment*
16	*History of SUSIM*

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SUSIM

Solar Ultraviolet
Spectral Irradiance Monitor

A Program to Study the Sun's Interaction with the Upper Earth Atmosphere

to be flown on the NASA space missions
UARS Upper Atmosphere Research Satellite and
ATLAS Atmospheric Laboratory for Application and Science

On October 10, 1946, Dr. Richard Tousey used a V-2 rocket to photograph for the first time the Sun's ultraviolet spectrum beyond the atmospheric cutoff. Ever since, the ultraviolet solar spectrum has been the focus of solar research at the Naval Research Laboratory. Over the decades, with NASA sponsorship, we have improved the absolute accuracy and precision of photometric ultraviolet measurements. The two SUSIM instruments described in this publication represent the culmination of this effort. To be launched on NASA spacecraft in 1991 and 1992, these instruments are ready in time to participate in a major research effort to explain the chemistry, dynamics, and energetics of the Earth's upper atmosphere. The increasing awareness that human activities destroy the ozone layer has made this research more urgent than it was at the time of its inception in 1978.

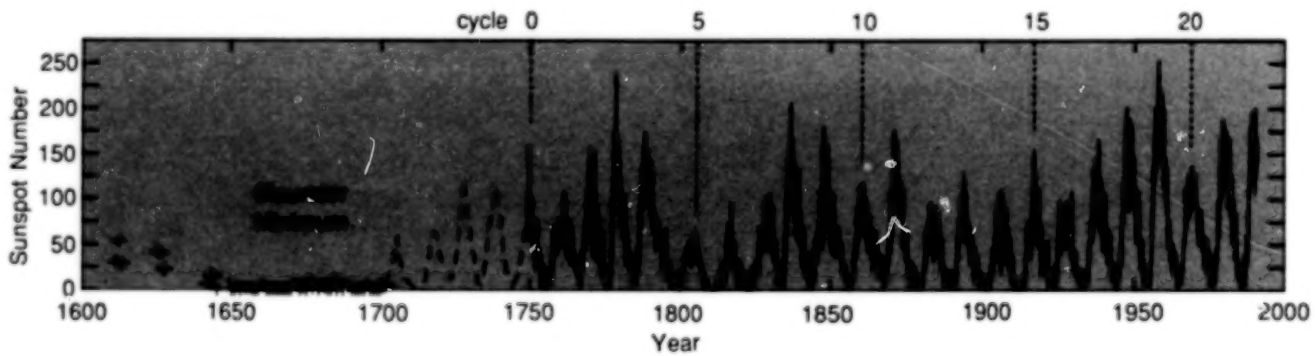
Guenter Brueckner
Judith Lean
Michael VanHoosier

Naval Research Laboratory

Systematic sunspot records date back to ancient China. Numerous naked-eye observations of sunspots have been recorded since 28 B.C., but systematic observations didn't begin until 1611 with the invention of the telescope. Four people share the honor of discovering sunspots through the telescope: Johan Goldsmid in Holland, Galileo Galilei in Italy, Christopher Scheiner in Germany, and Thomas Harriot in England. However, the periodicity of sunspots was not detected until the 19th Century. In 1843, Heinrich Schwabe in Germany announced his discovery of a probable 10-year solar cycle. Wolf in 1856 finally determined the average length of the sunspot cycle to be 11.1 years.

Numerous dark spots regularly appear in the photosphere of the Sun, some with diameters many times that of the Earth. It is believed today that sunspots occur in the photosphere where very strong magnetic fields choke off most of the energy that is transported from the interior of the Sun by convection. As a result of less energy input, sunspots are darker and cooler than the surrounding photosphere. Solar magnetic activity also generates other phenomena that vary with the solar cycle: magnetic fields of lesser strength in the plages, which surround sunspots, actually result in a slightly increased brightness of the photosphere. The solar atmosphere above the plages shows strong enhancement of ultraviolet and X-ray emission, compared with the undisturbed quiet Sun.

The main purpose of the SUSIM instrument is to measure the changes in the solar output of ultraviolet radiation caused by solar activity over a period of a solar cycle and to answer the question: How strong is the solar output at different wavelengths at different times of the solar cycle? The answer to this question will determine how much of the variation in the ozone layer of the Earth's atmosphere is caused by natural influences from the Sun compared with changes caused by human activities through the release of chlorofluorocarbons.

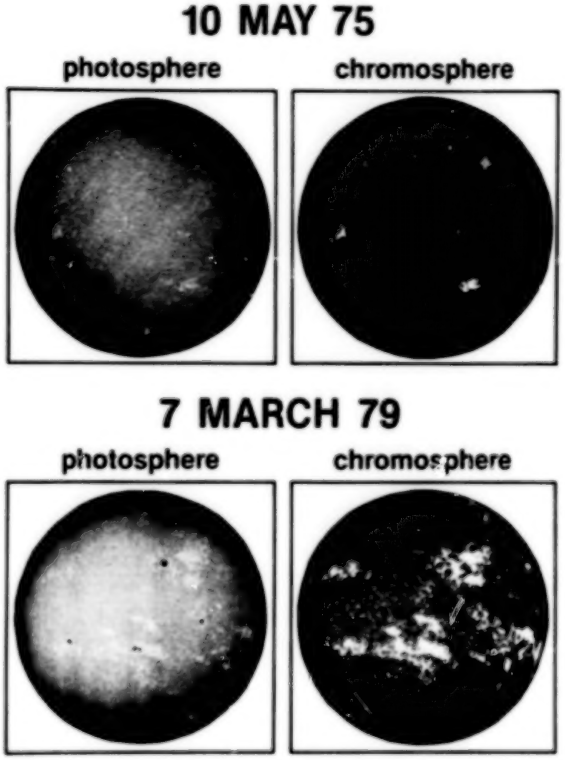


Sunspot numbers since the year 1610. Other solar indexes change together with the sunspot numbers. Increases in both the total solar output (the so-called *solar constant*) and the ultraviolet radiation of the Sun coincide with high sunspot numbers. Note the absence of solar activity in the 17th Century, which coincided with the coldest temperatures of the "Little Ice Age," a well documented global drop in temperature of an average of approximately 1° C.

Other solar phenomena also change with the solar cycle and couple the Sun with the magnetosphere and the atmosphere of the Earth. During the maximum of the sunspot cycle, powerful explosions—called solar flares—cause large clouds of protons to collide with the Earth's magnetic field causing geomagnetic storms. These storms are accompanied by the aurora borealis and occasionally can cause current surges in power lines paralyzing large power systems. In 1989, a large solar flare caused an 8-hour blackout of the whole province of Quebec in Canada.

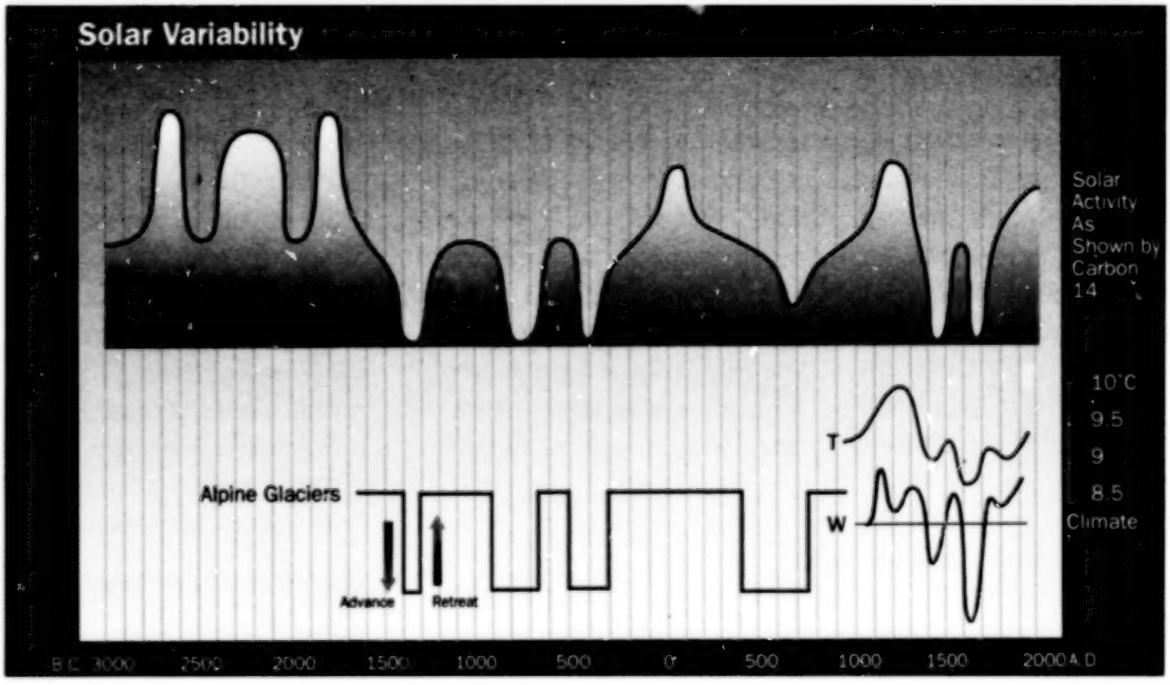
Another force coupling solar activity with the Earth's magnetosphere is the solar wind, which can disturb the Earth's magnetic field; this force, however, is not as violent as large solar flares. The solar wind is also modulated by the solar cycle, but not in phase. Flares and the varying solar wind modulate the upper atmosphere via currents induced by the unsettled geomagnetic field, while the ultraviolet radiation of the Sun heats the atmosphere directly. Precise measurements of the solar ultraviolet radiation, accompanied by intensive measurements of the Earth's upper atmosphere, should help to disentangle various cause-and-effect relationships between the Sun and the Earth. NASA's UARS mission has been designed to do exactly this.

Finally, it has been demonstrated recently that the total solar irradiance, or the *solar constant*, is not constant but variable with the solar cycle. Although the magnitude of the variation—approximately 0.1%—is too small to cause significant climatic changes on Earth, the possibility exists that larger variations of the total solar irradiance over longer periods might be responsible for larger global changes in the Earth's climate.

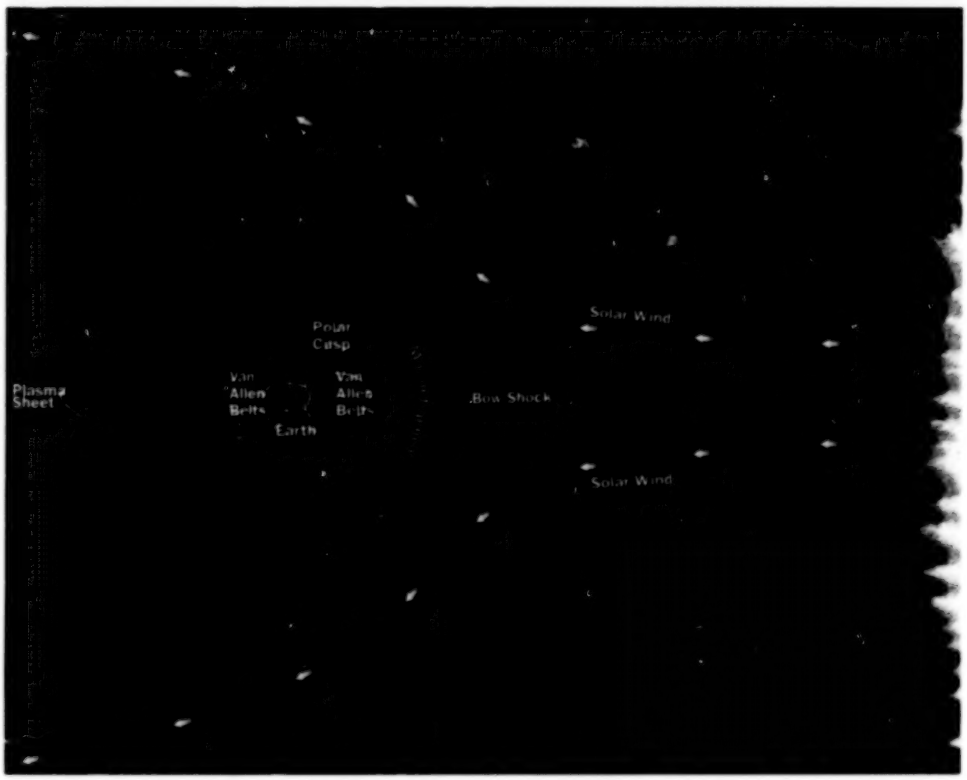


The photosphere and chromosphere at solar minimum (*top*) and maximum (*bottom*). The photosphere emits most of the total solar irradiance, which is variable over a solar cycle, because the radiation deficit of cooler sunspots is not balanced exactly by the radiation excess of hotter plages.

Ultraviolet radiation varies because it is emitted more strongly from plages, which disappear at solar minimum.



The carbon 14 content in tree rings can be used as a proxy for solar activity. The carbon 14 in the Earth's atmosphere varies because changes in the solar wind with solar activity modulate galactic cosmic rays. The mean annual temperature (T) and the extreme winter temperature (W) seem to be clearly correlated with solar activity. It is believed today that the 0.1% measured variability of the *solar constant* over a solar cycle is too small to be responsible for a 1° C change in climate. Other mechanisms could explain these climatic variations: a long-term (i.e., centuries) variability of the total solar irradiance, which is larger than the observed solar cycle variability; or, a nonlinear coupling mechanism on the Earth that results in a cooling when solar radiative output is consistently low. During such times of absent solar activity it is also possible that the diminished ultraviolet radiation can influence the Earth's climate. All this, however, remains speculative today (*NASA graphic*).



The solar wind interacts with the Earth's magnetosphere *(NASA graphic)*

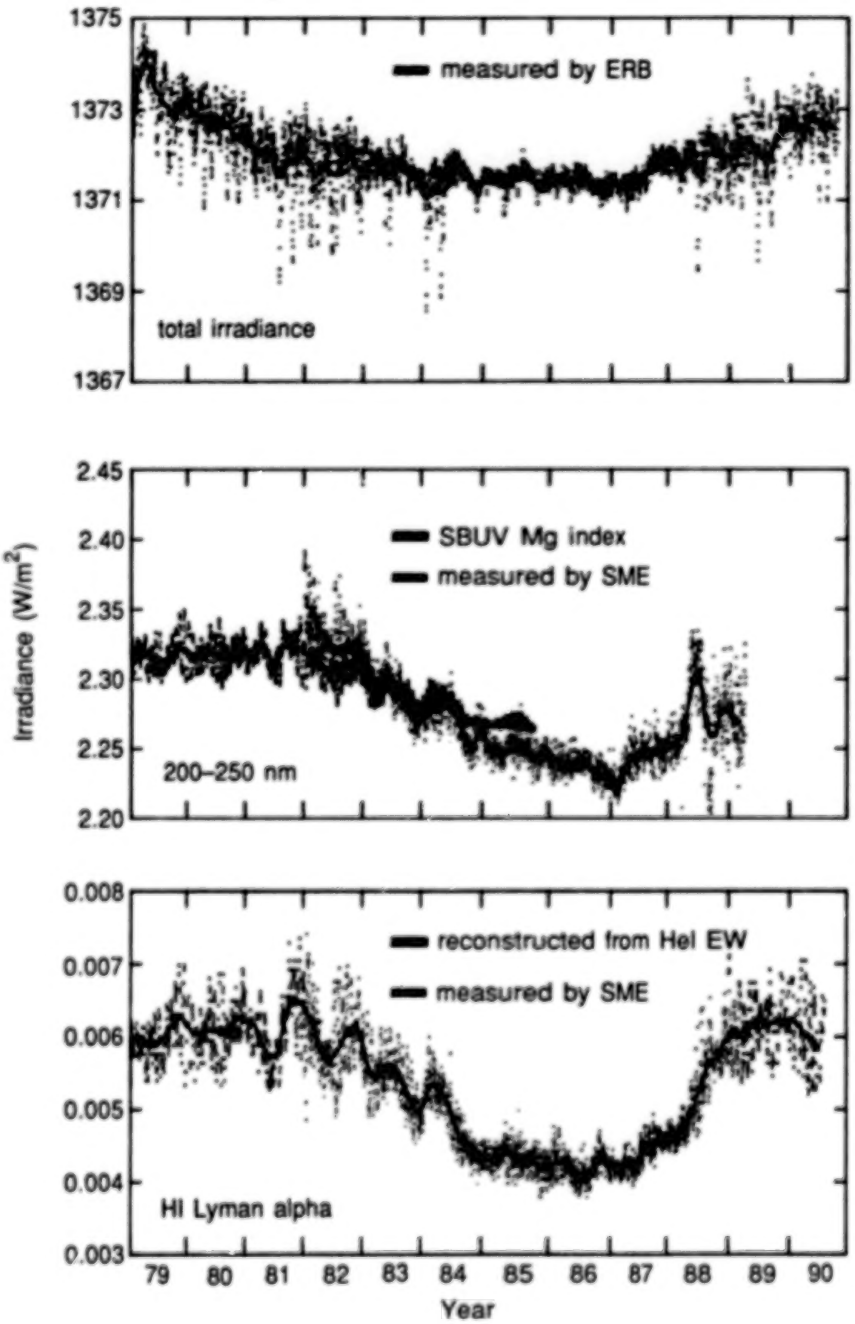
This painting by Brueghel recorded the unusual freezing of Dutch canals during the "Little Ice Age" that Europe experienced in the 17th Century

Only recently, satellite measurements have shown that the *solar constant* changes. The *solar constant* (or total solar irradiance) is a measure of the total radiative output of the Sun from X-ray wavelength to the infrared and was believed not to vary. Recent satellite measurements show two different periods of change:

a) The solar output changes over days when groups of large, dark sunspots cross the visible disk, thereby reducing the area of the solar disk that radiates at a temperature of about 5,500° K.

b) The solar output also exhibits variations over the solar cycle. Because at solar minimum, no sunspots are seen on the Sun, it was thought until recently that the solar output would be anticorrelated with solar activity, i.e., that the radiation would be stronger at solar minimum. Rather, the reverse has been found. The *solar constant* increases toward the solar maximum because the number of faculae, which are brighter than the undisturbed Sun, also increases toward the maximum. Speculation that the excess energy in the faculae compensates for the deficit energy in the sunspots and that, therefore, the energy production of the Sun is constant have also been disproved by recent satellite measurements. Although the changes in solar output over a solar cycle are only 0.1%, they indicate that variations with longer periods and larger amplitudes could exist. This scenario has recently obtained new credibility from measurements of solar-type stars. A few have been found to change their radiative output by as much as 0.4% over a period of 5 years. Could similar changes also occur in the Sun?

It is, therefore, important to continue *solar constant* monitoring indefinitely. The UARS will carry the Active Cavity Radiometer Irradiance Monitor (ACRIM) experiment, a successor of the Jet Propulsion Laboratory's ACRIM experiment on the Solar Maximum Mission satellite, which reentered the Earth's atmosphere in 1989. With UARS, this important monitoring effort can be resumed.



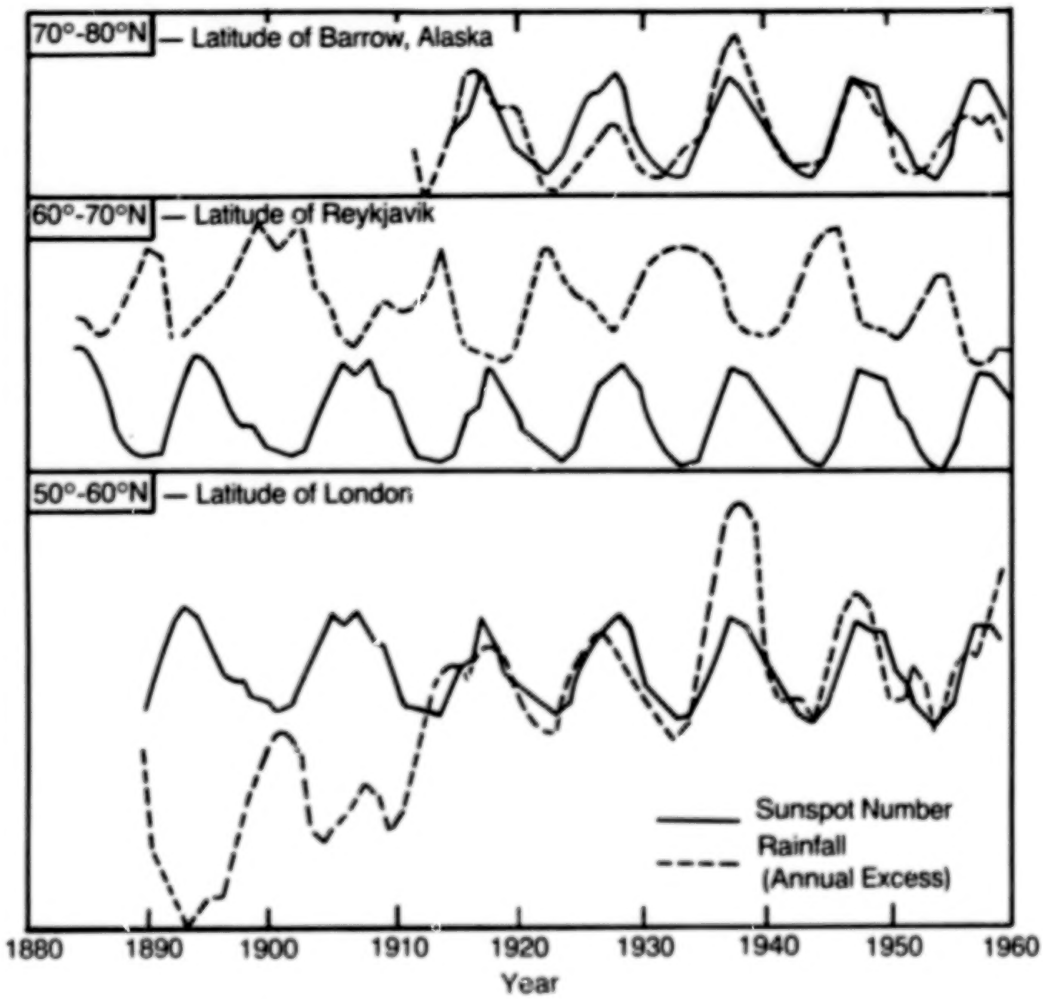
Solar cycle variability: *Top*: The total solar irradiance as measured by the Earth Radiation Budget (ERB) satellite. The total solar irradiance from solar maximum to minimum varies by 0.1%. The brief excursions of 0.1% to 0.3% are caused by the transit of large, dark sunspot groups. *Center*: The solar cycle variability of the ultraviolet radiation between 200 and 250 nm has been measured to be 4%. However, this result must be considered preliminary because of changing instrument sensitivities. The radiation in this wavelength band is absorbed primarily by ozone. As well, it dissociates fluorocarbons; it is therefore crucial for the existence of the ozone layer. *Bottom*: Variability of H-Lyman-α at 121 nm, the strongest emission line in the solar spectrum. From this figure, one derives a maximum-to-minimum ratio of 1.5. Factors of 2.5 to 3 have also been reported. To measure the radiation at 121 nm is particularly difficult because optical elements are easily "blinded" by only a few molecular layers of organic contaminants.

The solar output varies with the solar cycle and perhaps on longer time scales. Small variations of 0.1% are found in the total solar output. Climate models show that these variations are insufficient to significantly modulate the weather on Earth. However, local weather patterns—like precipitation—seem to correlate with the solar cycle (see opposite page). Such correlations are typically local, not global, and they come and go. Other local weather patterns show no correlation with the solar cycle. Are we overestimating the statistical validity of the correlation? Not for the correlations shown on the opposite page, which are statistically valid at more than a 90% confidence level. However, all but a few of the correlations between almost everything on Earth and the solar cycle had to be abandoned because they were statistically insignificant.

Climate models of the Earth do not include sophisticated feedback mechanisms that might enhance small solar changes in a nonlinear way. Such feedback mechanisms could either enhance or dampen the influence of solar output changes on the Earth. Cloud cover of the Earth is an example. A very small warming of the Earth caused by small changes in solar radiation might produce more clouds, which would in turn reduce the solar energy reaching the surface of the Earth, resulting in a negative feedback or damping out of solar influence. However, more clouds could generate additional heating of the atmosphere because they absorb infrared thermal radiation from the Earth, resulting in enhanced warming in response to small solar changes. Competing climate mechanisms are poorly understood.

Nor can a coupling between the Sun and the weather on Earth via changes in the Sun's output of ultraviolet radiation or particle bombardment of the upper atmosphere be ruled out. It is well known that the Earth's upper atmosphere and its embedded ionosphere expand toward solar maximum, driven by increased heating from excess solar ultraviolet radiation. In the stratosphere, the temperature and the ozone layer change throughout the solar cycle, also driven by solar ultraviolet output changes. Could these changes couple down to the troposphere, which regulates the weather? Because the energy stored per volume in the tropopause is 100 times greater than that in the upper atmosphere, simple energy arguments suggest not. But again, nonlinear mechanisms including radiative, chemical, or dynamical coupling may amplify solar changes.

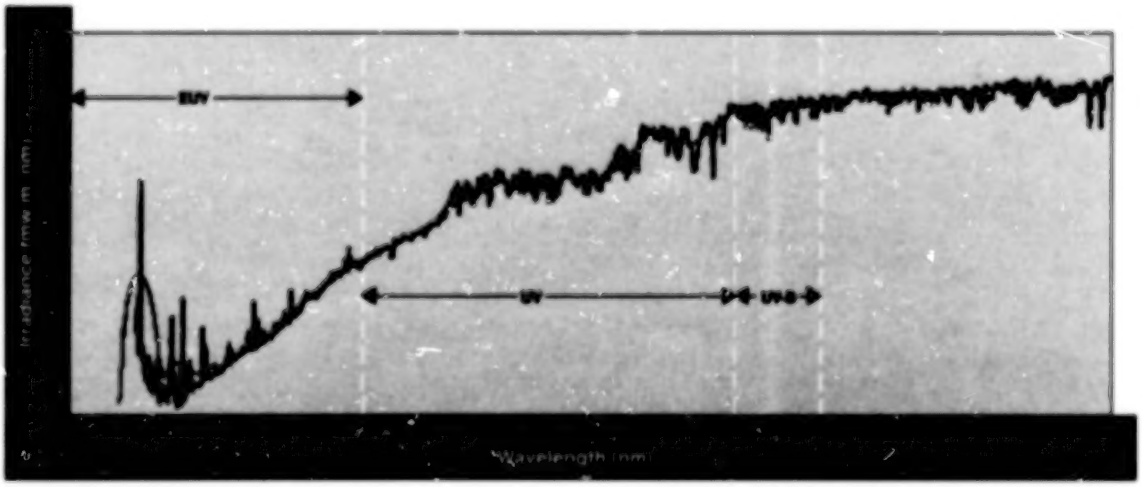
The comprehensive suit of instruments assembled on the UARS to simultaneously monitor the Earth's upper atmosphere and the Sun will be the most powerful tool ever employed to probe the Solar/Earth connection. The solar ultraviolet output to be monitored by the SUSIM experiment is only one of several parameters that couple the Sun with the Earth's atmosphere but is perhaps the most promising candidate for revealing a connection between the solar cycle and the weather.



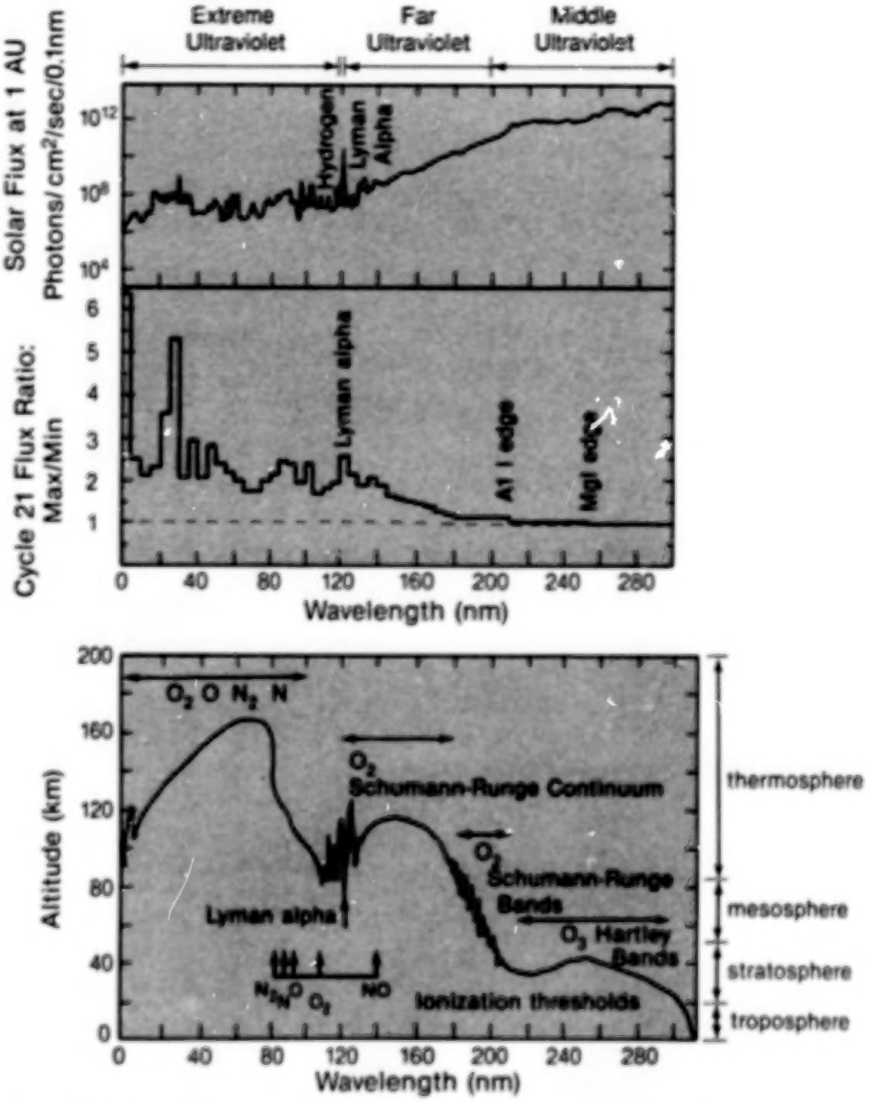
Solar effects on weather? Hundreds of correlations between the solar cycle and changing phenomena on Earth have been claimed, only to be abandoned because of poor statistical significance. The correlations and anticorrelations shown in this figure between the sunspot number and the annual excess rainfall at different locations are statistically significant. However, that does not mean that a cause-and-effect relationship exists between the Sun and the weather unless a credible physical mechanism is found for the Sun-weather coupling (*NASA graphic*).

As pointed out before, the upper atmosphere's energy comes from the Sun's ultraviolet radiation, energetic particles, and the Earth's infrared radiation, which is absorbed by molecules like carbon dioxide, water, and ozone. The Sun's ultraviolet radiation is the dominant energy input into this region, although it constitutes only 1% of the total solar irradiance.

While the total solar irradiance varies by only 0.1% over the solar cycle, the ultraviolet radiation changes by much more. Factors of 1.5 to 2.5 at 121 nm (H-Lyman-α), 30% at 150 nm, 10% at 180 nm, and 5% at 250 nm have been estimated. However, accurate measurements of the absolute solar ultraviolet radiative output are extremely difficult. Ultraviolet radiation shining on an optical element of a photometer changes its sensitivity by reacting with residual organic hydrocarbon molecules and "baking" them onto the optical surface. Because the resulting carbon molecules are opaque at ultraviolet wavelength, only a few molecular layers will "blind" a photometer. This is the reason why past measurements have failed to provide reliable values for the variability of the Sun's ultraviolet output. Consequently, new, self-calibrating spectrophotometers have now been built to distinguish between real changes in solar output and sensitivity changes of the instrument. SUSIM is the most advanced of this new generation of ultraviolet spectrophotometers. A multitiered system of checks, which consists of excessive optical redundancy and four calibration light sources, has been built into the instrument. A "shell game" will be played with redundant optical channels, whereby some channels are used much less than others to protect them from being blinded. Yet another check will be made on the measurements of the SUSIM experiment on UARS; periodic flights of a second, freshly calibrated SUSIM instrument on the Space Shuttle ATLAS series will provide independent cross-calibration.



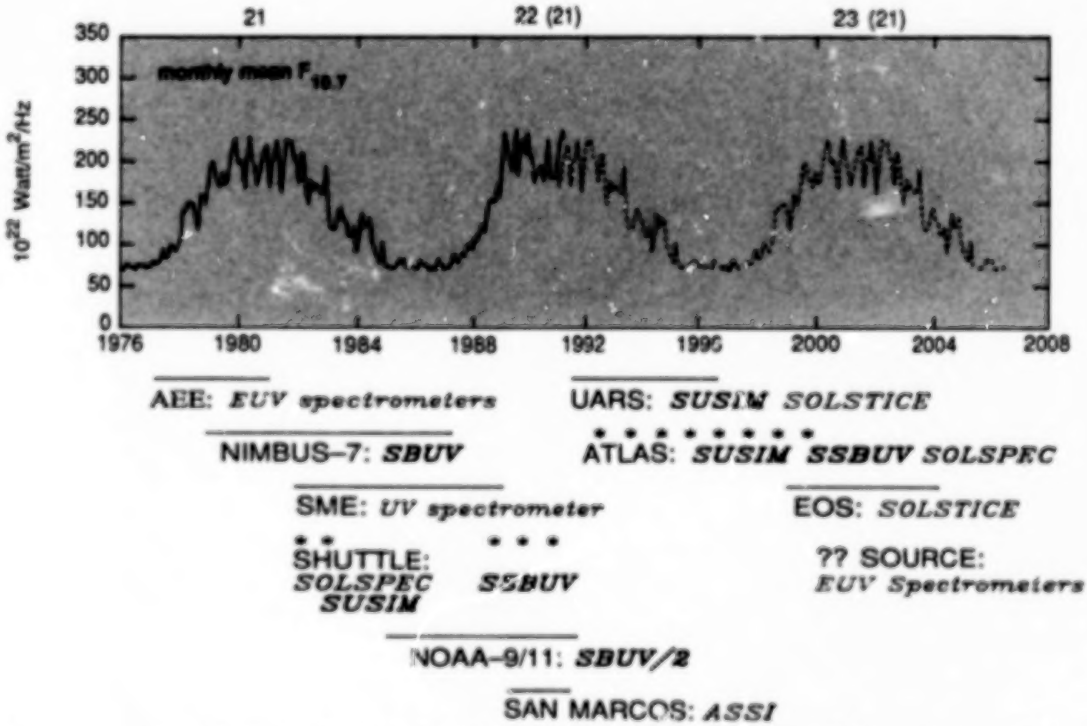
Solar ultraviolet radiation. The ultraviolet radiation at $\lambda < 180$ nm is absorbed high in the atmosphere primarily by atomic and molecular oxygen. At longer wavelengths, between 180 and 290 nm, UV is absorbed by either O_2 or O_3; weak O_3 absorption between 290 and 320 nm permits biologically damaging UV-B to reach the surface. As O_3 is depleted, the UV-B at the surface increases rapidly, causing higher incidences of skin cancer and other harmful effects on the biosphere.



The solar ultraviolet spectrum (*top*), its variability (*center*), and the absorption of this radiation in the Earth's atmosphere (*bottom*). From the H-Lyman-α line at 121 nm toward the atmospheric cutoff at 300 nm, the intensity of the solar spectrum increases by four orders of magnitude. At the same time, its solar cycle variability decreases by two orders of magnitude. The center graph, which shows estimated values for the variability of the Sun's ultraviolet output from the maximum of the solar cycle to the minimum H-Lyman-α at 116 nm, varies by a factor of 2. Toward longer wavelengths, the variability declines to a few percent at 250 nm. Ultraviolet light of different wavelengths is absorbed by different molecules at different altitudes in the Earth's atmosphere. This radiation governs the primary chemical, radiative, and dynamic processes that occur in the atmosphere above the troposphere. To understand these processes, a precise knowledge of the intensity and the variability of the solar ultraviolet input is needed. These are exactly the measurements that the SUSIM instrument will carry out.

This publication deals primarily with one of the three main processes that govern the upper atmosphere—the radiative energy input from the Sun. But only the simultaneous study of all three processes (energetics, chemistry, and dynamics) will reveal the detailed processes that comprise the upper atmosphere system.

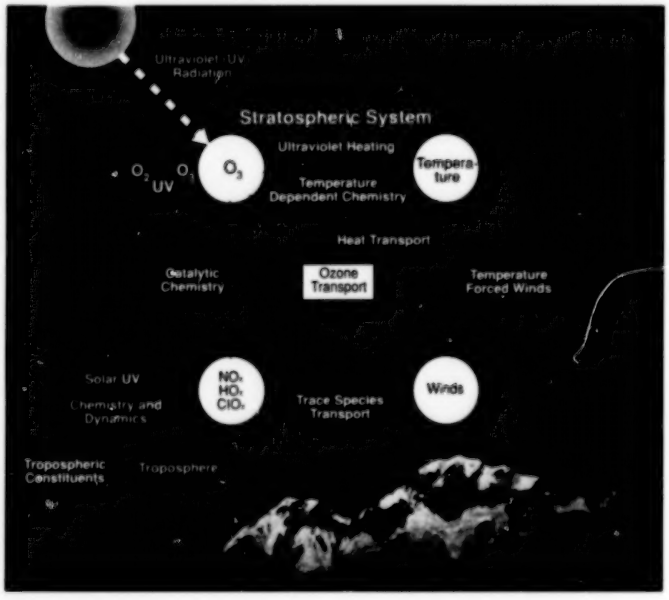
The UARS satellite has been designed with this goal in mind. While the SUSIM experiment measures the solar ultraviolet output, other instruments will map minor atmospheric constituencies such as ozone and the radical species that destroy it. Ozone is created by the reaction between molecular and atomic oxygen. This process is initiated when solar ultraviolet radiation at wavelengths less than 240 nm dissociates molecular oxygen via the Schumann-Runge bands to produce atomic oxygen. But ozone is also destroyed by subsequent absorption of solar ultraviolet radiation via the Hartley bands from 240 to 300 nm. This absorption provides the dominant energy input to the stratosphere, driving the dynamic motions that continually circulate the atmospheric constituents. This picture illustrates the delicate balance between chemical minor constituents and the solar



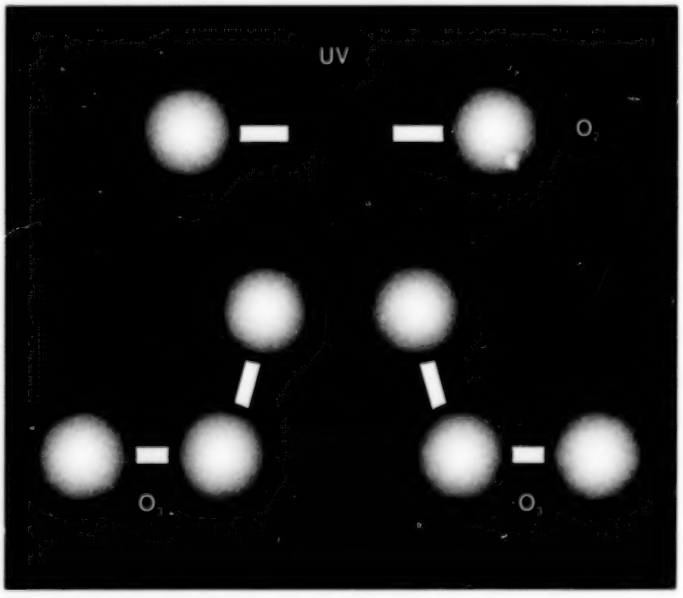
Past, present, and future solar ultraviolet irradiance measurements from different spacecraft. SUSIM on UARS will be accompanied by a second solar ultraviolet irradiance instrument, SOLSTICE, which uses as reference standards measurements of the stars. The UARS satellite has a design lifetime of 3 years, but hopefully will live longer. To recalibrate the SUSIM instrument on UARS and to bridge ultraviolet measurements from the UARS era to the launching of the Earth Observing System (EOS), the second SUSIM instrument will be flown periodically on the Space Shuttle. This allows new calibrations to be made between flights.

ultraviolet radiation. The release of chlorofluorocarbons into the atmosphere has changed this balance. CFCs are inert gases that do not react chemically in the lower atmosphere, allowing them to reach the stratosphere where they are broken up by solar ultraviolet radiation near 200 nm. As a result, chlorine atoms are released, which act as catalysts in ozone-destroying reactions. Consequently, a very small amount of chlorine can destroy a very large number of ozone molecules, because in a catalytic reaction chlorine is not bound to any other atom.

This catastrophic experiment of mankind with our planet was recognized in 1974. In 1978, NASA began its UARS program, but it was another 7 years before the first evidence of the ozone destruction was found: the spring ozone hole over Antarctica. None of the atmospheric models had predicted this phenomenon, because these models did not then account for the enhanced destruction of ozone by chlorine reactions that occur on surfaces (clouds) rather than in gases. Nor had they predicted the transport of chlorine from its primary northern hemisphere midlatitude sources to the Antarctic. Instruments on UARS will be able to measure numerous chemical species that participate in ozone chemistry, as well as the winds in the stratosphere that transport these trace constituents. This will be crucial for a quantitative understanding of the upper atmosphere.



Stratospheric system. Of prime concern is maintenance of the stratospheric ozone layer, which shields terrestrial life from damaging solar ultraviolet radiation (*NASA graphic*).



Ozone formation begins with dissociation of diatomic O_2 molecules by ultraviolet radiation; the free oxygen atoms combine with other O_2 molecules to form triatomic ozone (O_3) (*NASA graphic*).

The SUSIM instruments are precision ultraviolet spectrometers that incorporate redundant optical paths and in-flight calibration deuterium (D_2) lamps to provide accurate recording of solar spectral irradiance from 120 to 410 nm and the tracking of any instrument ultraviolet sensitivity changes.

Multiple methods of measurement are built into the SUSIM to ensure that any changes in its optical elements, detectors, or calibration sources can be distinguished. This allows the evaluation of the true instrument sensitivity that is needed during flight to produce accurate, absolute solar ultraviolet spectral irradiance values.

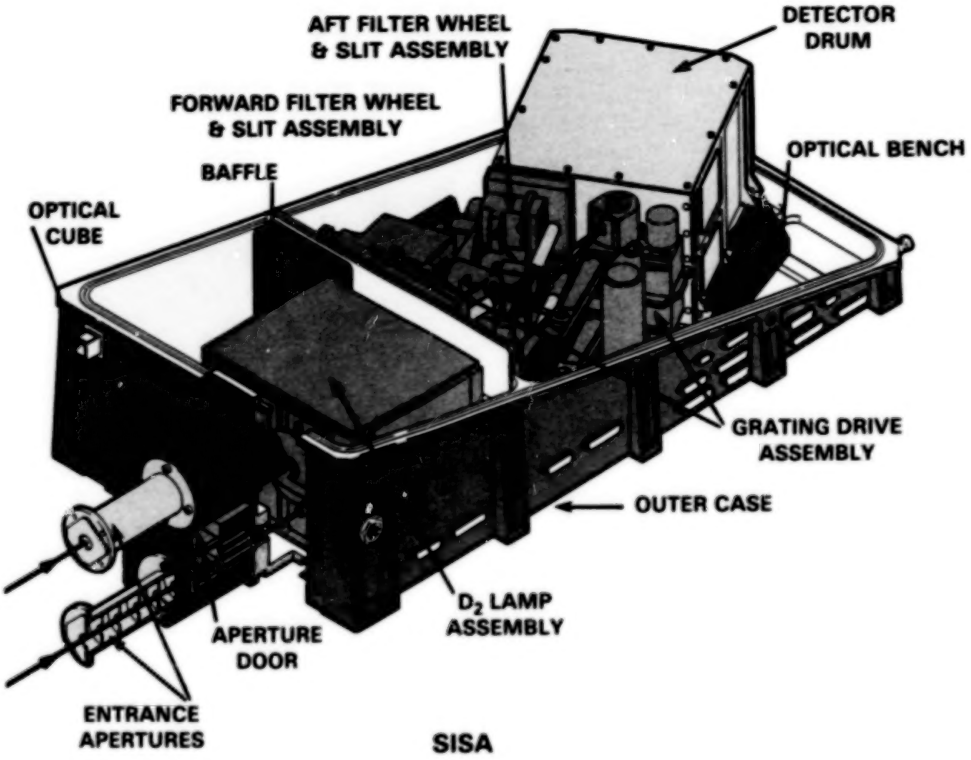
The determination of absolute sensitivity is performed at the National Institute of Standards and Technology's Synchrotron Ultraviolet Radiation Facility (NIST-SURF). The necessity to measure the sensitivity with all possible combinations of elements requires weeks of effort and extensive reduction of the data collected. The instrument has five detectors, two spectrometers—each with two different spectral resolutions—neutral density filters, and second-order suppression filters. The instrument also must be measured for angular response within its field of view. To complete these measurements, the response of the instrument to nearly totally polarized light produced by the synchrotron must be measured.

This absolute calibration is then extended by using a D_2 lamp, which has been calibrated by the National Physics Laboratory (NPL) and by NIST. The D_2 lamp is used primarily to permit the tracking of sensitivity changes during integration and testing, and during flight. D_2 lamps are carefully selected for aging and operational stability prior to the calibrations. Vibration tests at flight levels are performed on the lamps, and selection of the lamp with the minimum change is made.

The sensitivity of the instrument in the longer wavelength region (250 to 400 nm) is cross-checked by using quartz halogen tungsten lamps to calibrate the instrument at NRL. These lamps are calibrated by NIST to approximately 1% absolute accuracy.

For the SUSIM/UARS experiment, an inflight calibration will be performed monthly with one of its four D_2 lamps, every six months with a second lamp, and yearly with a third lamp. All four lamps will be operated soon after the instrument is activated in orbit so that the fourth lamp is available to replace any lamp that may disagree with the other lamps.

The SUSIM/UARS instrument will have the added advantage of a long flight duration with periodic cross-calibrations from SUSIM/ATLAS underflights. With the ability to calibrate both prior to flight and after retrieval of the SUSIM/ATLAS, a very high absolute accuracy can be obtained and then applied to update the accuracy of the SUSIM/UARS experiment.



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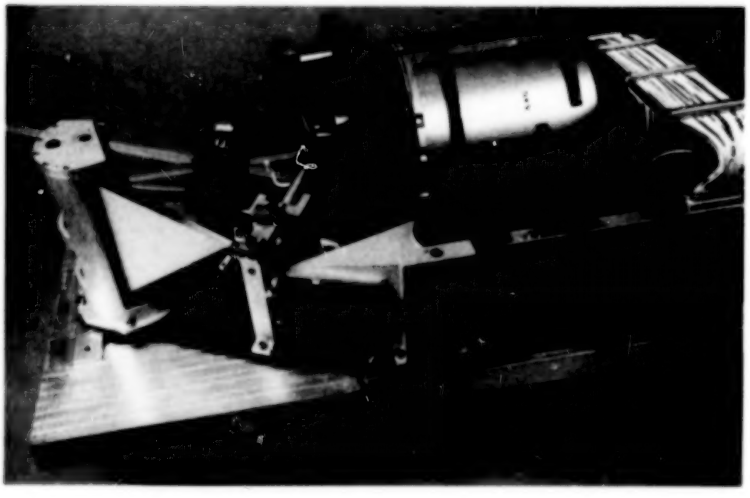
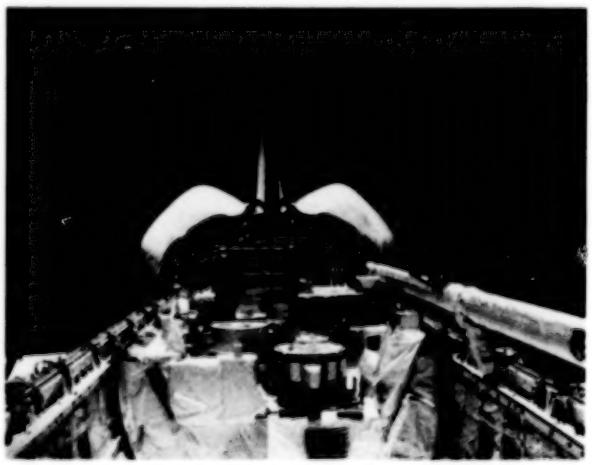
The SUSIM/UARS instrument, shown with the case lid off, comprises two double-dispersion spectrometers with a common scanning mechanism inside a hermetically sealed case that provides much of the contamination protection

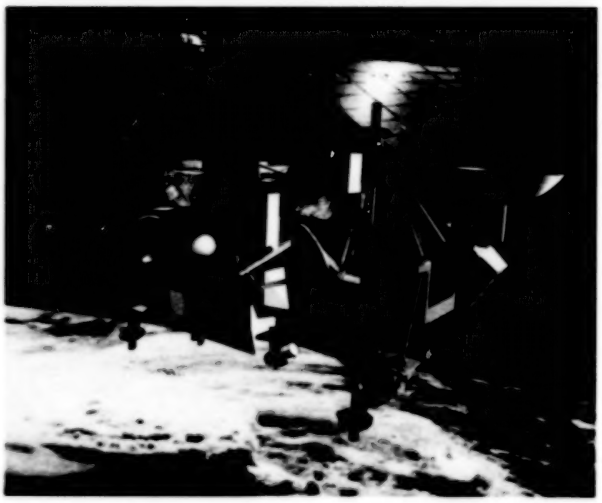


The SUSIM/ATLAS instrument shown without its external case. The red laser beam shows the path through which the Sun's rays travel.

In 1977, NRL's Solar Physics Branch conceived the SUSIM experiment to fulfill the pressing scientific need for accurate solar irradiance measurements. In response to NASA's call, during the next few years the SUSIM instrument was designed, fabricated, tested, and calibrated for flight on the Space Shuttle. It was first flown on the Office of Space Science and Applications' OSS-1 "Pathfinder Mission" as the primary payload on Space Shuttle flight 3 in March 1982. The Spacelab 2 mission in July 1985 provided a second flight, when SUSIM was placed with three other solar instruments, including the NRL High Resolution Telescope and Spectrograph, on the Instrument Pointing System. This same Space Shuttle instrument, now called SUSIM/ATLAS, is scheduled to fly in March 1992 as part of the ATLAS-1 payload and will then refly at approximately one year intervals with the ATLAS follow-on series of missions. These many flights will provide the snapshots of accurate solar irradiance data for long-term solar variability determination and for underflight calibration of the UARS instrument.



The OSS-1 pallet in the Space Shuttle payload bay collecting solar irradiance data (*NASA photo*)



The upcoming SUSIM flight on the UARS mission to be launched on STS 48 in September 1991 will operate 600 km above the Earth in an orbit inclined 57° to the Equator. This orbit will permit the UARS to provide essentially global coverage of the stratosphere and mesosphere. Ten UARS experiments will provide the most complete data on energy inputs, winds, and chemical composition ever gathered. Taken together, the data set will yield the first simultaneous, comprehensive global coverage of these closely coupled atmospheric properties.

With radiation from the Sun as the dominant influence on the upper-atmospheric processes, the SUSIM/UARS is an important part of both the energy input experiment group and the UARS mission. Virtually all of the solar ultraviolet radiation in the wavelength range 120 to 300 nm is absorbed in the stratosphere, mesosphere, and lower thermosphere. This energy, together with particle energy inputs at high latitudes, is fundamental to the photochemistry and dynamics of the upper atmosphere. Solar UV heating and particle energy deposition, combined with cooling by emission in the thermal-infrared spectral region, produce most of the seasonal, vertical, and latitudinal variability of the atmosphere's thermal structure, which in turn controls the dynamics of the upper atmosphere (*NASA photo*).

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S.B. Shipley
Mechanical Technician

The Spacelab 2 Instrument Pointing System positioning the four instruments for a period of solar measurements (*NASA photo*)

REVIEWED AND APPROVED
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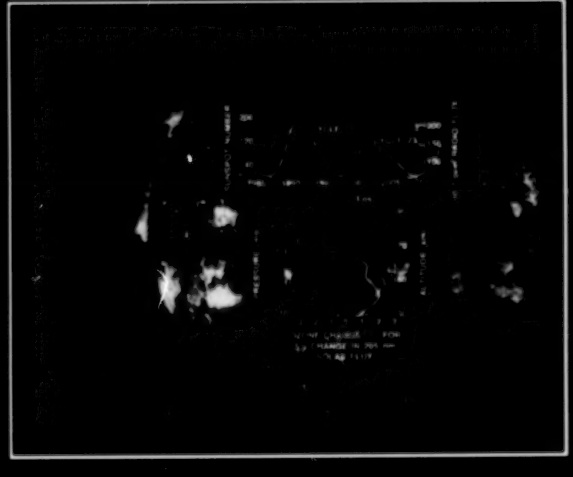
Superintendent, Space Science Division



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